| REPORT DOCUMENTATION PAGE | *Form Approved* *OMB No. 0704-0188* |
|---|---|



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From - To)* |
|---|---|---|
| 31-10-2007 | Final Report | 01-12-2002 to 31-08-2007 |

**4. TITLE AND SUBTITLE**
Characterizing Variability in the Distribution of High-Frequency Acoustic Backscattering in a Shallow Water Coastal Region

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**
N00014-03-1-0212

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Lawson, Gareth, L
Stanton, Timothy, K
Wiebe, Peter, H

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Woods Hole Oceanographic Institution
Woods Hole, MA
02543

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Office of Naval Research
800 N. Quincy St.
Arlington, VA
22217

**10. SPONSOR/MONITOR'S ACRONYM(S)**
ONR

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Distribution Unlimited

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The physical and biological factors underlying variability in the distribution of high-frequency acoustic volume backscattering stemming from zooplankton in shallow water coastal regions were examined, with particular emphasis on krill on the Antarctic continental shelf. Improved parameterization of a theory-based krill scattering model was achieved through direct measurement of all model parameters. Methods were developed and verified for acoustically distinguishing krill aggregations from other zooplankton, and estimating krill length, abundance, and biomass. Application of these methods to multi-frequency volume backscattering measurements made during surveys of an Antarctic study region in fall and winter 2001 and 2002 demonstrated strong seasonal, inter-annual, and spatial variability in the distribution of both krill and overall zooplankton biomass. These findings have important implications to the fields of both zooplankton acoustics and ecology, especially in relation to the interactions of the krill with its predators.

**15. SUBJECT TERMS**
Ocean acoustics, backscattering, zooplankton, krill, distribution, Antarctic

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)* |
|---|---|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UL | 7 | Lawson, Gareth, L / 831-655-6237 |

**FINAL REPORT**

**GRANT #**: N00014-03-1-0212

**PRINCIPAL INVESTIGATORS**: Drs. Gareth L. Lawson, Timothy K. Stanton and Peter H. Wiebe

**INSTITUTION**: Woods Hole Oceanographic Institution

**GRANT TITLE**: Characterizing Variability in the Distribution of High-Frequency Acoustic Backscattering in a Shallow Water Coastal Region

**AWARD PERIOD**: 1 December 2002 - 31 August 2007

**OBJECTIVES**: The central purpose of this ONR Graduate Traineeship Award in Ocean Acoustics was for the Primary Investigator, Gareth Lawson, to design, execute, and defend his doctoral dissertation research, with the Co-Primary Investigators, Timothy K. Stanton and Peter H. Wiebe, acting as advisors. In terms of its scientific goal, the project examined the physical and biological factors underlying variability in the distribution of high-frequency acoustic volume backscattering stemming from zooplankton. The specific research objectives were:

1. To quantify spatial and temporal variability in zooplankton distribution, and hence the distribution of uncertainty in the acoustic field, in shallow water coastal regions.
2. To assess the predictability and persistence of such patchiness, and understand its association with physical and biological oceanographic processes.
3. To continue the process of field-testing and refining zooplankton scattering models.

**APPROACH**: The overall approach was to apply the models of zooplankton scattering developed previously at Woods Hole Oceanographic Institution (WHOI) to multi-frequency volume backscattering data collected in continental shelf regions under other research projects, in order to identify dominant scatterers and estimate zooplankton size, abundance, and biomass. These estimates were then compared between times and regions to assess patterns in variability. The areas under study included a continental shelf region west of the Antarctic Peninsula and the Gulf of Maine. At both sites, the data used for analysis were collected with the WHOI BIo-Optical Multi-frequency Acoustical and Physical Environment Recorder (BIOMAPER-II).

The project ultimately came to focus on variability in the distribution of krill (primarily *Euphausia superba* and *E. crystallorophias*) in the Antarctic study region. An important aspect of the research involved the development and testing of protocols for distinguishing the scattering of krill from other zooplankton taxa, delineating krill aggregations within the acoustic record, and estimating the size, abundance, and biomass of aggregation members. These methodologies were applied to acoustic data collected in the Antarctic during fall and winter surveys conducted by the Southern Ocean Global Ecosystem Dynamics (GLOBEC) program. The resulting estimates of krill distribution and aggregation structure were then related to features of the physical and biological environment measured concurrently during the surveys.

**ACCOMPLISHMENTS**: The work accomplished under this award made important contributions to the fields of both zooplankton acoustics and ecology, and resulted in four publications with the Primary Investigator as senior author and seven as co-author.

Analyses of the distribution of volume backscattering strength at 120 kHz in the Antarctic continental shelf study region revealed strong seasonal and spatial variability during the falls and winters of 2001

and 2002, much of which was understandable in light of the likely effect of meso-scale circulation on the distribution of zooplankton scatterers (Lawson *et al.*, 2004). Four general types of scattering features were evident: 1) large bottom-associated patches found in coastal regions of variable bathymetry, 2) smaller discrete patches found primarily in the surface mixed layer across much of the shelf, 3) deep diffuse patches found near the shelf-break, and 4) deep homogeneous scattering layers situated over much of the southern portion of the study area. Predictions of expected volume backscattering strength based on depth-stratified net samples and taxon-specific scattering models, in combination with analyses of Video Plankton Recorder observations, suggested that the first two feature types stemmed from krill (*Euphausia* spp.) aggregations (Lawson *et al.*, 2004; in press a). Net catches and BIOMAPER-II measurements of target strength suggested that myctophid fishes were the dominant scatterer in the third feature type. The available evidence concerning the deep scattering layers was less conclusive, but they appeared to consist of a complex mixture of zooplankton scatterer types, perhaps dominated by copepods and gas-bearing siphonophores (Lawson *et al.*, 2004).

Similar analyses of multi-frequency volume backscattering data (43, 120, 200, and 420 kHz) collected with the BIOMAPER-II in the Gulf of Maine during the falls of 1997-1999 under projects funded in part by ONR and in part by NOAA revealed strong inter-annual and spatial variability, both of which differed between acoustic frequencies. Mean backscattering levels did not reflect the decrease in the abundance of the ecologically-important copepod *Calanus finmarchicus* observed in net catches in the fall of 1998 relative to the falls of 1997 and 1999. An increase in the abundance of the predators and competitors of *C. finmarchicus* may have served to keep backscattering levels high during this period. Distinct patterns and diel changes were evident in the vertical distribution of backscattering, although these differed between basins and years. Collaborative work with Dr. Andone Lavery of WHOI suggested that at certain locations in this Gulf of Maine study region, gas-bearing siphonophores dominated scattering at all four BIOMAPER-II frequencies (Lavery *et al.*, in press). Otherwise, no single zooplankton scatterer type dominated volume backscattering at all frequencies considered.

Following these initial analyses, the present project came to focus on krill (primarily *Euphausia superba* and *E. crystallorophias*) at the Antarctic study site. This decision was made in part because these animals form acoustically-identifiable aggregations within which they dominate scattering at all four BIOMAPER-II frequencies, making the estimation of biological parameters like krill abundance and size from four-frequency data a relatively straightforward problem. The decision also related to the fact that the Antarctic field work began at the same time as the Primary Investigator was formalizing his dissertation research plan. Focusing on the Antarctic study site thus allowed him to be involved in both data collection and analysis, unlike the Gulf of Maine study site where the data were collected some years earlier.

Much of the initial work of the project made use of existing scattering models and parameterizations for interpreting observed backscattering levels. In the case of Antarctic krill, however, an investigation was made into improving the parameterization of a Distorted-Wave Born Approximation (DWBA) based scattering model (Lawson *et al.*, 2006). Direct measurements made with a Video Plankton Recorder were used to constrain the key parameter governing the orientation of the animal relative to the incident acoustic wave. Recently published length-based regressions were used to constrain the animal's acoustic material properties, rather than the earlier approach of using single parameter values for all lengths. The newly-parameterized model produced predictions of krill target strength more consistent with *in situ*

measurements than earlier parameterizations. These predictions were smaller, however, than expected under the semi-empirical model traditionally used to estimate krill target strength. Use of this semi-empirical model in estimating krill abundance would result in estimates too low by a factor of at least 2.75.

With this fully-parameterized and field-tested scattering model in hand, methods were next developed and refined for identifying krill aggregations and estimating krill length, abundance, and biomass on the basis of multi-frequency acoustic data alone, without recourse to net samples (Lawson *et al.*, in press a). A biologically-based threshold level of volume backscattering strength for identifying krill aggregations was derived on the basis of krill visual acuity and estimates of the minimum density of krill over which a given individual could maintain a visual association with its nearest neighbor, and thereby with the aggregation as a whole. Differences in mean volume backscattering strength at 120 and 43 kHz further served to distinguish krill from other sources of scattering. A multi-frequency inverse method was developed to estimate the mean length and numerical density of krill in these acoustically-identified aggregations on the basis of measurements of mean volume backscattering strength (43, 120, 200, and 420 kHz). The biomass density of krill was then estimated based on measurements of volume backscattering strength at 120 kHz, the mean length of krill estimated from the multi-frequency inversion, the target strength in relation to length model of Lawson *et al.* (2006), and the wet weight-to-length relationship measured by Wiebe *et al.* (2004). Measurements were also made of certain features (e.g., position, shape, internal structure) of each identified krill aggregation.

These methods were tested at locations where independent information on the presence of krill as well as on krill length and abundance were available from Video Plankton Recorder observations and net catches from a 1-$m^2$ Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS). Comparison of the results of the inverse analysis to net samples were favorable in the case of estimated mean krill length (within a margin of error of 3-12%). Acoustic estimates of krill numerical density, however, exceeded those from nets by one to two orders of magnitude, likely due primarily to net avoidance and secondarily to differences in the volumes sampled by the two systems. The potential for multi-frequency data and mathematical inverse techniques to be used for the simultaneous and quantitative estimation of zooplankton abundance and size has been known for some time, but to the best of our knowledge, this project marks the first time that such methods have been applied to broad-scale data from Antarctic krill surveys.

Application of these methods to multi-frequency survey data collected during the fall and winter 2001 and 2002 surveys at the Antarctic study site with the BIOMAPER-II demonstrated strong seasonal, inter-annual, and spatial variability in the distribution of krill (Lawson *et al.*, in press b). The distribution of krill aggregations was characterized by many small aggregations closely spaced relative to one another, punctuated by much fewer aggregations of very large size that accounted for the majority of overall biomass in the region. Generalized additive models indicated that high krill biomass was consistently associated with regions close to land where the temperature maximum below 200 m in depth was cooler than was available over the shelf as a whole. Krill were thus not associated with regions where intrusions of warm and nutrient-rich circumpolar deep water onto the shelf were present, despite such intrusions being thought to be an important driver of primary productivity in the region.

Finally, the morphology, internal structure, and vertical position of individual krill aggregations were examined in relation to a variety of

properties of the physical and biological environment. Krill aggregations were observed to exhibit diel changes in vertical position and biomass density, with aggregations deeper and denser during the day than during the night. Such diel vertical migrations had not previously been observed for krill during winter. Concurrent observations of chlorophyll *a* concentrations (an index of phytoplankton abundance) and the occurrence of predators together reinforced the conclusion that aggregation and diel vertical migration represent strategies to avoid visual predators, while also allowing the krill access to shallowly-distributed food resources.

In addition to the main dissertation research project, the Primary Investigator was involved in a number of collaborations, examining the distribution of higher predators in the Antarctic (including seabirds, seals, and whales) in relation to their krill and zooplankton prey (Friedlaender *et al.*, 2006; Ribic *et al.*, in press), as well as examining the distribution and behavior of Antarctic krill and other zooplankton using nets (Ashjian *et al.*, 2004; Wiebe *et al.*, 2004) and a Video Plankton Recorder (Ashjian *et al.*, in press).

**CONCLUSIONS**: 1. At certain acoustically-identifiable times and locations in the Antarctic study region, krill were the dominant scatterer at all four BIOMAPER-II frequencies (43, 120, 200, and 420 kHz). This makes the krill a favorable species for study with multi-frequency acoustics.
2. Away from these locations, other zooplankton dominated scattering, especially copepods and gas-bearing siphonophores. This suggests that the assumption often made in acoustic surveys for Antarctic krill that all scattering stems from krill is inappropriate, and care must be taken to identify properly those exact locations where krill are responsible for observed scattering.
3. Strong spatial and inter-annual variability in volume backscattering was observed at the Gulf of Maine study site. Ongoing analyses are addressing the causes of these inter-annual changes.
4. Antarctic krill were observed to orient themselves mostly horizontally, or at normal acoustic incidence relative to a vertically-oriented echosounder. Parameterization of a DWBA-based scattering model for krill with the observed distribution of angles of orientation and direct measurements of all other necessary parameters led to target strength predictions highly similar to *in situ* measurements.
5. Multi-frequency inversions can be used successfully to estimate Antarctic krill length and abundance over large survey areas without recourse to net samples.
6. Highest Antarctic krill biomass during fall of both survey years was consistently associated with regions close to land where temperatures below 200 m in depth were cooler than what was available over the shelf as a whole.
7. Krill aggregation and diel vertical migration represent strategies to avoid visual predators during the day, while also allowing the krill access to shallowly-distributed food resources by night.

**SIGNIFICANCE**: This project has resulted in a detailed understanding of variability in the distribution of zooplankton volume backscattering, particularly in the case of Antarctic krill. Ultimately this should allow such variability to be modeled and predicted. This constitutes an essential step in constraining the uncertainty introduced into Navy representations of the acoustic field by these important scatterers, and in understanding the implications of zooplankton patchiness to the distribution of higher predators, including marine mammals and exploited fish species. Much of the present research has made use of existing scattering models. Through comparisons of acoustic data to video and net samples, an approximate model for Antarctic krill has been further evaluated and better parameterized. The outcome is a field-validated acoustic scattering model of a complex, naturally occurring scatterer.

**PATENT INFORMATION**: None.

**AWARD INFORMATION**:

1. The Primary Investigator, Gareth Lawson, successfully defended his doctoral research and received his Ph.D. in September 2006.

2. Outstanding Student Paper Award to Gareth Lawson, American Society of Limnology and Oceanography/American Geophysical Union Ocean Sciences Meeting, 2006.

**PUBLICATIONS AND ABSTRACTS** (for total period of grant):

**Publications**


1. Lawson, G.L., P.H. Wiebe, T.K. Stanton, and C.J. Ashjian. Euphausiid Distribution Along the Western Antarctic Peninsula - (A) Development of Robust Multi-Frequency Acoustic Techniques to Identify Euphausiid Aggregations and Quantify Euphausiid Size, Abundance, and Biomass. Deep-Sea Research II. [accepted, refereed]

2. Lawson, G.L., P.H. Wiebe, C.J. Ashjian, and T.K. Stanton. Euphausiid Distribution Along the Western Antarctic Peninsula - (B) Distribution of Euphausiid Aggregations and Biomass, and Associations With Environmental Features. Deep-Sea Research II. [accepted, refereed]

3. Lawson, G.L., P.H. Wiebe, C.J. Ashjian, D. Chu, and T.K. Stanton. 2006. Improved parameterization of Antarctic krill target strength models. Journal of the Acoustical Society of America, 119: 232-242. [published, refereed]

4. Lawson, G.L., P.H. Wiebe, C.J. Ashjian, S.M. Gallager, C.S. Davis, and J.D. Warren. 2004. Acoustically-inferred zooplankton distribution in relation to hydrography west of the Antarctic Peninsula. Deep Sea Research II, 51: 2041-2072. [published, refereed]

5. Lavery, A.C., P.H. Wiebe, T.K. Stanton, G.L. Lawson, M.C. Benfield, and N.J. Copley. Determining dominant scatterers of sound in mixed zooplankton populations. Journal of the Acoustical Society of America. [in press, refereed]

6. Ashjian, C.J., C.S. Davis, S.M. Gallager, P.H. Wiebe, and G.L. Lawson. Distribution of larval krill and zooplankton in association with hydrography in Marguerite Bay, Antarctic Peninsula, in austral fall and winter 2001 described using the Video Plankton Recorder. Deep-Sea Research II. [accepted, refereed]

7. Ribic, C.A., E. Chapman, W.R. Fraser, G.L. Lawson, and P.H. Wiebe. Winter distributions of seabirds and pinnipeds in Marguerite Bay, Antarctica, and their relationship to environmental features. Deep-Sea Research II. [accepted, refereed]

8. Wiebe P.H. and G.L. Lawson. 2007. Acoustic sampling on the US SO GLOBEC survey cruises. GLOBEC International Newsletter, 13(1): 57-59. [published, non-refereed]

9. Friedlaender, A.S., P.N. Halpin, S. Qian, G.L. Lawson, P.H. Wiebe, D. Thiele, and A.J. Read. 2006. Whale distribution in relation to prey abundance and oceanographic processes in shelf waters of the Western Antarctic Peninsula. Marine Ecology Progress Series, 317: 297-310. [published, refereed]

10. Ashjian, C.J., G.A. Rosenwaks, P.H. Wiebe, C.S. Davis, S.M. Gallager, N.J. Copley, G.L. Lawson, and P. Alatalo. 2004. Distribution of zooplankton on the continental shelf of Marguerite Bay, Antarctic

Peninsula, during austral fall and winter, 2001. Deep Sea Research II, 51: 2073-2098. [published, refereed]

11. Wiebe, P.H., C. Ashjian, S. Gallager, C. Davis, G.L. Lawson, and N. Copley. 2004. Using a high powered strobe light to increase the catch of Antarctic krill. Marine Biology, 144: 493-502. [published, refereed]

**Published Abstracts**

1. Lawson, G.L. 2007. Distribution, patchiness, and behavior of Antarctic zooplankton, assessed using multi-frequency acoustic techniques. Journal of the Acoustical Society of America, 121: 1255.

2. Lawson, G.L., P.H. Wiebe, T.K. Stanton, and C.J. Ashjian. 2006. Development and application of multi-frequency acoustic techniques to the study of Antarctic krill distribution. Journal of the Acoustical Society of America, 120: 3108.

3. Lawson, G.L., P.H. Wiebe, T.K. Stanton, and C.J. Ashjian. 2006. Krill Patch Structure and Distribution Along the Western Antarctic Peninsula, With Comparison to the Gulf of Maine. Eos Trans. AGU, 87, Ocean Sci. Meet. Suppl., Abstract OS34H-05.

4. Lawson, G.L., P.H. Wiebe, C.J. Ashjian, C.S. Davis, S.M. Gallager, and D. Chu. 2003. A multi-sensor approach to identifying the sources of zooplankton acoustic backscattering data collected on the Southern Ocean GLOBEC broad-scale cruises. Eos Trans. AGU, 84, Ocean Sci. Meet. Suppl., Abstract OS21B-02.

5. Lavery, A.C., G.L. Lawson, and P.H. Wiebe. 2005. Lessons learned from multifrequency acoustic studies of zooplankton and micronekton in the western Antarctic Peninsula and the Gulf of Maine. Journal of the Acoustical Society of America 118: 1908.

6. Lavery, A.C., P.H. Wiebe, R.W. Schmitt, T.K. Stanton, T. Ross, G. Lawson, N. Copley, K.E. Fisher, and F. Wolk. 2004. High-frequency acoustic volume scattering from zooplankton and moving oceanic microstructure. Journal of the Acoustical Society of America 115: 2583.

7. Ross, T., A. Lavery, R. Lueck, P. Wiebe, and G. Lawson. 2004. Ocean acoustic backscattering: When you can ignore acoustic scatter from turbulence and when you can't. Journal of the Acoustical Society of America 115: 2583.

8. Ashjian, C.J., P.H. Wiebe, C.S. Davis, S.M. Gallager, G.L. Lawson, and P. Alatalo. 2003. Demise of a Phytoplankton Bloom on the Continental Shelf Near Marguerite Bay, Antarctic Peninsula, in April-May, 2002 Observed With the Video Plankton Recorder and High Frequency Acoustics. Eos Trans. AGU, 84, Ocean Sci. Meet. Suppl., Abstract OS51J-01.

9. Chapman, E.W., C.A. Ribic, W.R. Fraser, G.L. Lawson, P.H. Wiebe, and C.J. Ashjian. 2003. Associations Between Seabird Distribution and Physical and Biological Oceanographic Features During Winter, 2001 in the Marguerite Bay Area on the Western Antarctic Peninsula. Eos Trans. AGU, 84, Ocean Sci. Meet. Suppl., Abstract OS12F-05.

10. Chu, D., P.H. Wiebe, G.L. Lawson, and N.J. Copley. 2003. Estimation of Antarctic krill biomass using a non-linear inversion technique. Eos Trans. AGU, 84, Ocean Sci. Meet. Suppl., Abstract OS51E-10.

11. Wiebe, P.H., M.F. Baumgartner, D. Mountain, M.C. Benfield, C.H. Greene, A.C. Lavery, N.J. Copley, and G.L. Lawson. 2003. Variation in the size of the overwintering population of Calanus finmarchicus in the Gulf of Maine during 1997, 1998, and 1999: Driven by changes in NAO

forced advection or local predator and competitor fields? Eos Trans. AGU, 84, Ocean Sci. Meet. Suppl., Abstract OS21B-03.

**RELATED PROJECTS**: The development of the BIOMAPER-II and its use in the Gulf of Maine cruises examined here were funded in part by the ONR (Grant Numbers N00014-95-11102, N00014-98-1-0362, and N00014-97-1-0646), and in part by NOAA (Grant 31654-5717). Additional data under analysis were collected with the BIOMAPER-II in the Antarctic, as part of the Southern Ocean GLOBEC program (NSF Office of Polar Programs Grant OPP-9910307). Some of the methodologies developed in the present project are also being applied to data collected during the U.S. Georges Bank GLOBEC program, as part of synthesis analyses funded by NOAA (Cooperative Institute for Climate and Ocean Research Grant NA17RJ1223). The zooplankton scattering models employed and extended in the project were originally developed under a number of ONR-funded projects (primarily Grant N00014-95-1-0287).